SUSPENDED SEDIMENT DISCHARGE IN SUBSURFACE FLOW FROM THE HEAD HOLLOW OF A SMALL FORESTED WATERSHED, NORTHERN JAPAN

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ABSTRACT

Surface flow and suspended sediment discharge from the head hollow of the Jozankei Experimental Watershed in Hokkaido, northern Japan, were measured to clarify the implications of subsurface hydrology for soil movement. Subsurface discharges during the extremely large storms of 1993 to 1994 were measured in a V-notch weir installed at a natural spring near the bottom of the head hollow, and shallow groundwater levels were observed in the wells excavated in the hollow. Sediment samples whose particle size range from 0·001 to 0·1mm were manually and automatically collected at 15 to 60 min intervals, by use of 1 or 2l polyethylene bottles. Maximum concentration and flux of suspended sediment during the storms preceded the peak discharge of subsurface flow by several hours. Neither the changes in concentration (mg l^{-1}) nor flux (mg s^{-1}) of suspended sediment coincided with those in subsurface discharge ($l s^{-1}$). Furthermore, sediment concentration was poorly correlated with the rate of change in subsurface discharge ($l s^{-2}$) during the rising limb of the hydrograph. Suspended sediment flux during the acceleratory limb, however, was closely correlated with the rate of change in subsurface discharge. The relationship between suspended sediment flux and rate of change in subsurface discharge were in inverse proportion to initial subsurface discharge before the storm runoff and they represented rare seasonal variation. Subsurface hydraulic erosion and transport of suspended sediment resulting from changes in rate of change in subsurface discharge actively occur during the acceleratory rising limb of the hydrograph. Accordingly, subsurface hydraulic erosion during the acceleratory rising limb of the hydrograph can be physically understood by analysing suspended sediment flux associated with rate of change in subsurface discharge and initial subsurface discharge.

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INTRODUCTION

Various hydrogeomorphic processes at the channel head provide topographic diversity of head and valley development (Dietrich and Dunne, 1993). Slope soil commonly piles up in the bottom of the valley following shallow landslides. This repeated geomorphic process brings about the formation of the head hollow by the creation of a relatively thick soil layer which retains a large capacity for water storage. Thus surface flow rarely occurs at the valley head hollow in humid and forested drainage basins except in the case of heavy rainfall. Subsurface discharge usually removes and redistributes the sediment in the valley head. This geomorphic process reveals that subsurface hydraulic erosion transforms the topography of the valley head in the long term, that is, it shows that subsurface discharge from the head hollow is one of the significant agents in valley development.

Subsurface hydraulic erosion is an important geomorphic process in the head watershed, because soil piping and water discharge via the pipes significantly affect hillslope hydrology, channel initiation and hillslope evolution (e.g. Jones, 1971, 1978, 1978a; Beven and Germann, 1982), as well as gully extension by tunnel scour erosion (e.g. Jones, 1987b; Swanson *et al.*, 1989; Garland and Humphrey, 1992). Sapping sediment yield from the soil pipes contributes to the convex configuration of the hillslope (Onda, 1994).

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The physical action of subsurface flow which causes sapping erosion is affected by changes in hydraulic gradient (Dunne, 1980; Yasuhara *et al*., 1984; Terajima and Sakura, 1993). This is essential for the hydrology and geomorphology of the slope, and the formation of microtopography in the head watershed resulting from subsurface discharge and sediment delivery (Sakura *et al*., 1987). Additionally, theoretical considerations about soil movement caused by subsurface discharge emphasize the effect of subsurface flow on slope failure (Terzaghi, 1943; Zaslavsky and Kassife, 1965; Kochel *et al*., 1985; Iverson and Major, 1986). Slope profiles and contrasts in hydraulic conductivity have the most pronounced and diverse effects on groundwater seepage force, effective stress, and slope failure potentials (Reid and Iverson, 1992). Simulations and experiments on soil movement attributed to seepage force and to sapping erosion demonstrate the importance of hydraulic head distribution in layered slopes for the mostly homogeneous and cohesionless soil (Rulon *et al*., 1985; Howard and Mclane, 1988). Additionally, one-dimensional model experiments related to the progressive erosion of the levees derive the relationship between seepage force, cohesion of the soil and the radius of the failure region (Kohno *et al*., 1987).

Many corroborative results regarding the interaction between subsurface hydrology and subsurface soil movement are of sufficient importance to be related to data sets measured in many places in the world. The authors measured suspended sediment discharge in subsurface flow from the head hollow of the Jozankei Watershed in Hokkaido, northern Japan, and considered the characteristics of sediment discharge in order to quantify the process of subsurface hydraulic erosion at the valley head. Suspended sediment was selected as an indicator for the observation and analysis of the interaction between subsurface discharge and sediment movement for the following reasons.

(1) Suspended sediment discharge emphasizes the initial stage of subsurface hydraulic erosion, because turbid subsurface water containing suspended sediment flowed out from the slope before a landslide initiation (Sassa, 1984). Furthermore, movement of suspended sediment from the soil surface preceded movement of sand particles by several minutes in a hydraulic experiment related to fluidization (Terajima and Sakura, 1993).

(2) Fine grained particles are the primary source of sediment in typical subsurface flows from valley heads; movement of bedload materials may be initiated after extensive flushing of fine sediment from the soil matrix (i.e. suspended sediment).

EXPERIMENTAL WATERSHED

Outline

Figure 1 shows the location and topography of the experimental watershed (Jozankei Watershed (43°N, 141°E). The watershed is situated 20 km west of Sapporo, and includes only one first-order stream that is a tributary to the Otarunai River.

The geology of the watershed is quartz porphyry intruded as a metamorphic rock during the Miocene period (Geological Survey of Hokkaido, 1980). The surface layer on the slope consists of the weathering products of the basement rock (like decomposed granite). Few flat surfaces occur on the ridges, and neither volcanic deposits nor terrace sediments overlie the ridges. Much angular gravel (>0·3 m in diameter), originating from the basement rock, accumulates to a thickness of 1 to 1·5 m on some ridges.

The watershed has an area of about 0·02 km^2, a relief of 129 m with a minimum elevation of 312 m at the Wt-weir, an average slope gradient of 36.7°, and an average stream bed gradient of 16°. Although the basement rock is exposed along the stream bed, colluvial soil from the side slope covers portions of the bed. The perennial spring is located at a distance of 150 m down from the crest slope. The drainage area contributing to the spring is about 0·011 km^2, corresponding to 55 per cent of the total watershed area. The head hollow details are given in the next section.

Vegetation in the watershed is a mixed conifer–hardwood forest, typical of this cool-temperate region, composed mostly of Todo fir (*Abies sachalinensis*) and Mizunara oak (*Quercus mongolica*). The understory vegetation and organic matter that originated from the trees cover the surface of the watershed. The A_0 layer of soil (organic horizon) is well developed.

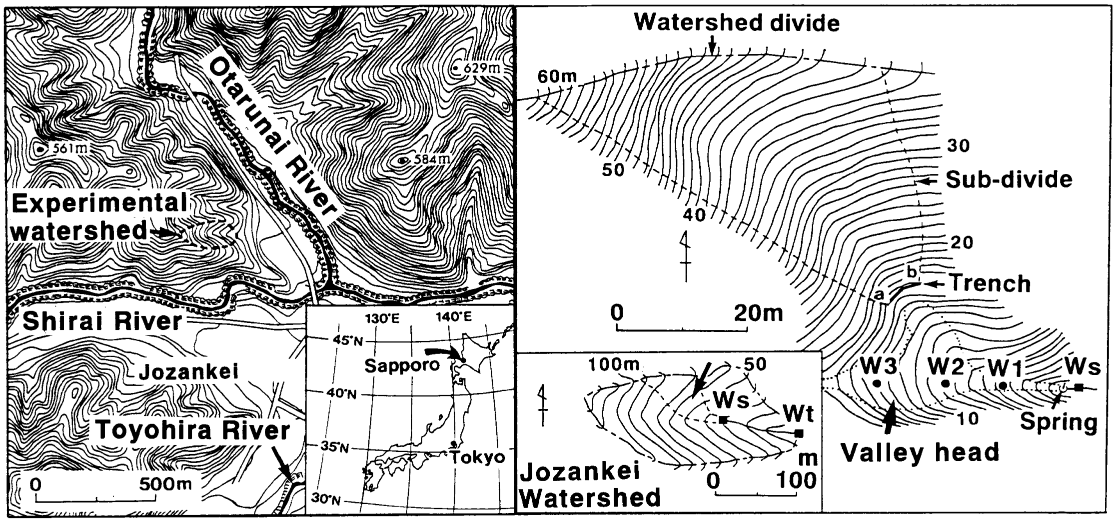

Figure 1. Location and topographic maps of the experimental watershed. Wt, weir for measuring stream discharge from the watershed; Ws, weir for measuring discharge from the head hollow; W1–W3, observation wells

Ambient temperature at the watershed ranges from −20°C in late January to 25°C in mid-July, and the average annual temperature is 7°C. Annual precipitation is about 1000 mm, with snow contributing about 45 per cent (typical precipitation in southern Japan, from 30°N to 40°N, ranges from 1500 to 3000 mm per year). Maximum accumulated snow depth is typically 2 m in early March. Stream discharge measured at the Wt-weir decreases during the snow-accumulation season from late November to late March, since little meltwater percolates from the bottom of the accumulated snow into the soil. There is usually considerable meltwater starting in late March or early April. In June and July, it is drier because of reduced rainfall and meltwater discharge (this is not typical of southern parts of Japan, where the rainy season occurs from mid-June to late July and more rain is also supplied by the typhoons which directly attack from summer to autumn). Much rain in Sapporo falls between August and early November due to low atmospheric pressures. Subsurface flow temperature measured at the spring in the Jozankei Watershed ranges from 0°C to 10°C. Pipe flow during the storm runoff occupies a maximum of 70 per cent of subsurface discharge from the side slope between weirs Ws and Wt (Kitahara and Nakai, 1992; Kitahara *et al*., 1993).

Head hollow

The head hollow in the valley head (see Figure 1) is 30 m long, a maximum of 15 m wide, and 10 to 20° in inclination. The upper part of the hollow gradually continues to the side slope (30 to 40° in inclination). The rill (5 m long and 0·3 m deep), including no flow, runs between the spring and well W1.

Figure 2 shows the schematic longitudinal soil profile of the head hollow along with values of saturated hydraulic conductivity (*Ks*) measured in 400 cm^3 soil cores for the A-horizon, a relatively shallow sandy layer and a middle clay-rich layer. The electrical conductivity measurement of subsurface discharge at the spring was used to estimate flow velocity in order to get the hydraulic conductivity value for a lower sand after salt has been inserted into well W1. The soil matrix consists mostly of particles of which the diameter observed at the soil section is below 5 mm, corresponding to fine pebbles. The maximum thickness of the soil layer is 3·6 m at well W3. The A-horizon ($Ks = 10^{-3}$ m s^{-1}) is less than 0·3 m. The underlying sedimentary soil is composed of three parts: (1) a relatively shallow sandy layer ($Ks = 10^{-4}$–10^{-5} m s^{-1}) containing much angular gravel (about 0·2 m in diameter); (2) a middle clay-rich layer ($Ks = 10^{-5}$–10^{-6} m s^{-1}) also containing much angular gravel (mostly below 0·2 m in diameter); and (3) a lower sand layer ($Ks = 10^{-3}$ m s^{-1}) with some angular gravel. These sediments are colluvial deposits from the side slope. The saturated hydraulic conductivity of the lower sand layer is greater

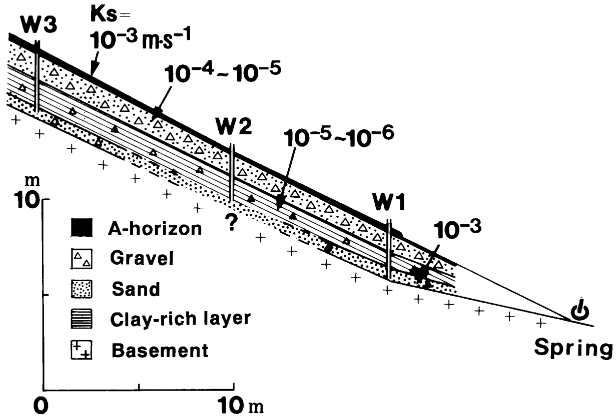

Figure 2. Longitudinal soil profiles of the head hollow. *Ks*, saturated hydraulic conductivity ($m\,s^{-1}$) of the sedimentary soil; W1–W3, observation wells

than that of the upper clay-rich soil. A more permeable zone, therefore, must be formed along the bottom of the sedimentary soil.

METHODOLOGY

Observations were conducted from 30 September 1993 to 5 November 1994. All observations of sediment discharge were discontinued during the winter season between December and mid-March because there was no suspended sediment discharge; this was a result of low subsurface flow discharges due to accumulated snow. Instrumentation within the watershed is shown in Figure 1. A 60° V-notch weir (Ws) was installed at 3 m below the spring and automatically measured water discharge from the head hollow. The rain gauge registered precipitation at 10 min intervals 20 m east of the Wt-weir. Potentiometers automatically recorded shallow groundwater level at 10 min intervals in the three wells (W1–W3).

Manual and automatic water sampling at the spring collected suspended sediment in subsurface flow during heavy rainfall from September 1993 to November 1994. During the observation period, the authors observed eight storms accompanied by suspended sediment yield in subsurface flow (see Tables I and II for details of the storms). Manual sampling required intervals of 15 to 60 min to collect water during storm runoff, and an automatic water sampling system (ISCO, model 2700) enabled observation at night. Since sediment with particle diameter of less than 0·1 mm flows down mostly as wash load (Egashira and Ashida, 1981), the following method was used to determine suspended sediment concentration in subsurface flow. The water samples were first passed through a 0·106 mm screen and then strained in a 0·001 mm glass fibre filter. The desiccation of the residual matter on the glass fibre filters required heating for 24 h at 80°C. Organic matter was then removed from the desiccated sediments by ashing for 30 min at 550°C in an electric furnace. The particle size of the remaining suspended sediments ranged from 0·001 to 0·106 mm, corresponding to clay to fine sand. Multiplying the subsurface discharge by suspended sediment concentration produced suspended sediment flux.

RESULTS

Subsurface discharge and suspended sediment yield

Figure 3 shows two typical cases of subsurface discharge from the head hollow, changes in suspended sediment concentration ($mg\ l^{-1}$) and flux ($mg\ s^{-1}$) on 22 October 1993 and on 16 September 1994. Total rainfall was 58 mm and maximum rainfall intensity was 10·5 mm h^{-1} (from 12:00 to 13:00) during the October storm in 1993, and corresponding values were 68 mm and 14·5 mm h^{-1} (from 9:00 to 10:00) during the September storm in 1994. Although these rainfall amounts were similar and these were very large storms for Hokkaido, northern Japan, overland flow was generated in the rill only from 11:45 to 15:30 on 16 September 1994, when the initial

Table I. Maximum ratio of sediment yields in subsurface flow from the valley head to total basin yields. See Table II and Figure 9 for the initial subsurface discharge (Q_i)

Storm	Maximum ratio of SSF*(%)	Notes†
30 Sep., 1993	0·003	Low Q_i
22 Oct., 1993	13·50	Figure 5a, low Q_i
27 May 1994	–	No data on suspended sediment discharge in stream flow
16 Sep., 1994	18·00	Figure 5b (overland flow generated)
23 Sep., 1994	5·39	Large Q_i
30 Sep., 1994	4·00	Middle Q_i
5 Oct., 1994	0·43	Middle Q_i
19 Nov., 1994	12·07	Middle Q_i

* SSF, suspended sediment flux

† Q_i, initial subsurface discharge

Table II. Linear correlation coefficient for the relationship between rate of change in subsurface discharge and suspended sediment flux during the rising limb of the hydrograph, coefficient α in Equation 3, and initial subsurface discharge prior to the storms

Storm	Linear correlation coefficient	α ($g\,s\,l^{-1}$)	Initial discharge ($l\,s^{-1}$)
30 Sep. 1993	0·93	20·99	0·007
22 Oct, 1993	0·88	73·48	0·005
27 May, 1994	0·94	20·98	0·115
16 Sep., 1994	0·91	19·32	0·031
23 Sep., 1994	0·95	8·18	0·205
30 Sep., 1994	0·99	7·28	0·126
5 Oct., 1994	0·98	3·92	0·115
19 Nov., 1994	0·94	29·60	0·110

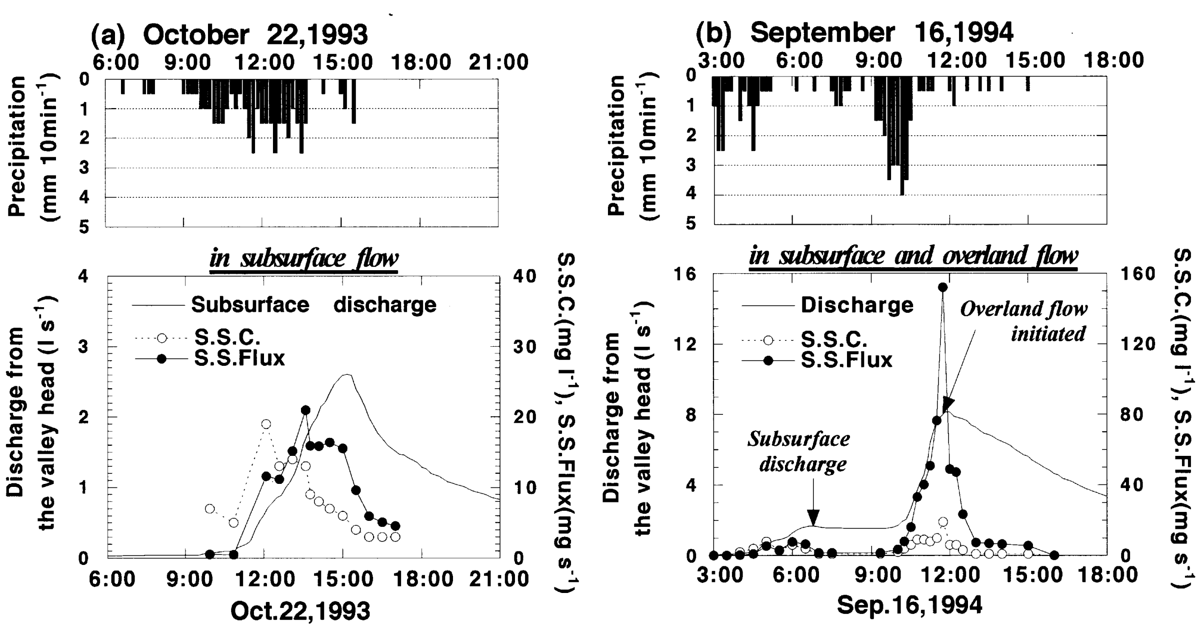

Figure 3. Water discharge from the head hollow and changes in concentration (SSC) and flux (SSFlux) of suspended sediment on (a) 22 October 1993 and (b) 16 September 1994

soil moisture condition, surmised from subsurface discharge prior to the storm, was more than that on 22 October 1993 (see Table II for initial subsurface discharge prior to the storm). Suspended sediment concentration and flux in subsurface flow preceded the peak discharge in subsurface flow by several hours,

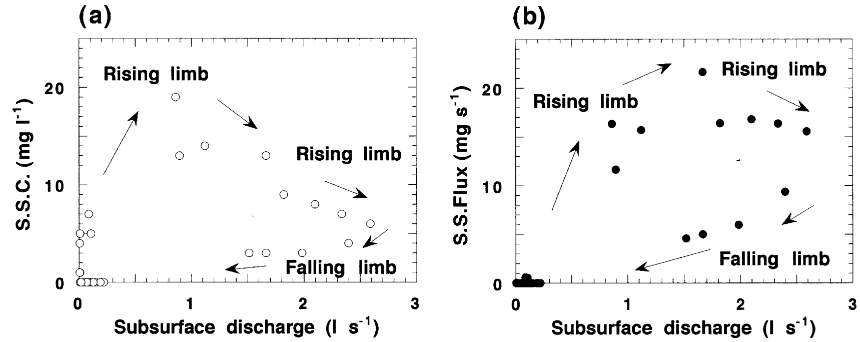

Figure 4. Relationship between subsurface discharge and suspended sediment on 22 October 1993: (a) suspended sediment concentration (SSC); (b) suspended sediment flux (SSFlux)

except in the case of overland flow initiation on 16 September 1994. The maximum value of suspended sediment flux, however, occurred a short time before the peak discharge in subsurface flow.

Figure 4 shows the relationships between subsurface discharge, suspended sediment concentration and flux on 22 October 1993. Although suspended sediment concentration and flux conspicuously increased on the initial rising limb of the hydrograph, both decreased close to 1–1·5 l s^{-1} of subsurface discharge. Suspended sediment concentration reduced notably to 0·3 times as much as its maximum concentration when subsurface flow showed peak discharge. During the falling limb of the hydrograph, both suspended sediment concentration and flux were lower than during the rising limb. Consequently, they represented clockwise hysteresis loops for a one-storm event.

The above facts (sediment discharge prior to subsurface flow and a clockwise hysteresis loop) were usually observed in the other six storms shown in Tables I and II. The characteristics of suspended sediment discharge in subsurface flow have something in common with observations in some rivers: for example, the observation in the small catchment in the United Kingdom by Walling (1974) and the measurement of suspended sediment concentration in the forested basin of the Bankei River, near Sapporo, Japan, by Kurashige (1985).

In the Jozankei Watershed, the characteristics of suspended sediment discharge in stream flow were summarized by Sakamoto *et al*. (1993, 1994). Suspended sediment concentration and flux preceded the peak in stream discharge and exhibited a clockwise hysteresis loop, suspended sediment flux correlated with stream discharge during the falling limb of the hydrograph, and the time lag between peaks in stream discharge and suspended sediment was smaller than that in subsurface discharge as shown in Figure 3.

Thus, during the falling limb, suspended sediment in subsurface flow may also be evaluated from the change in subsurface discharge. This is because during the rising limb of the hydrograph, suspended sediment discharge in subsurface flow is not simply based on the change in subsurface discharge.

Relative importance of valley head yields to total basin yields

Figure 5 and Table I show the relative importance of subsurface yields to total basin yields regarding sediment discharge. The drainage area contribution to the spring corresponds to 55 per cent of the total watershed area. If the ratio, therefore, exceeds the 55 per cent entered in Figure 5, water and sediment discharge from the valley head greatly affect those from the total watershed.

Water discharge from the valley head contributed considerably to stream discharge during the falling limb of the stream hydrograph (Figure 5). When saturated overland flow was initiated on 16 September 1994, water discharge from the valley head affected the total discharge from the watershed as soon as stream discharge formed the peak. In contrast, the effect of the suspended sediment discharge from the valley head on the total sediment discharge from the watershed appeared during the rising limb of the stream hydrograph. Additionally, suspended sediment discharge in subsurface flow (Figure 5a) contributed to total sediment discharge and exceeded 10 per cent during the falling limb of the stream hydrograph. However, the ratio of suspended sediment flux was at most 13·5 per cent (24·3 per cent per unit drainage area) in the case of subsurface discharge (Figure 5a, Table I) and hardly exceeded 18 per cent (32·4 per cent per unit drainage area) even in the case of

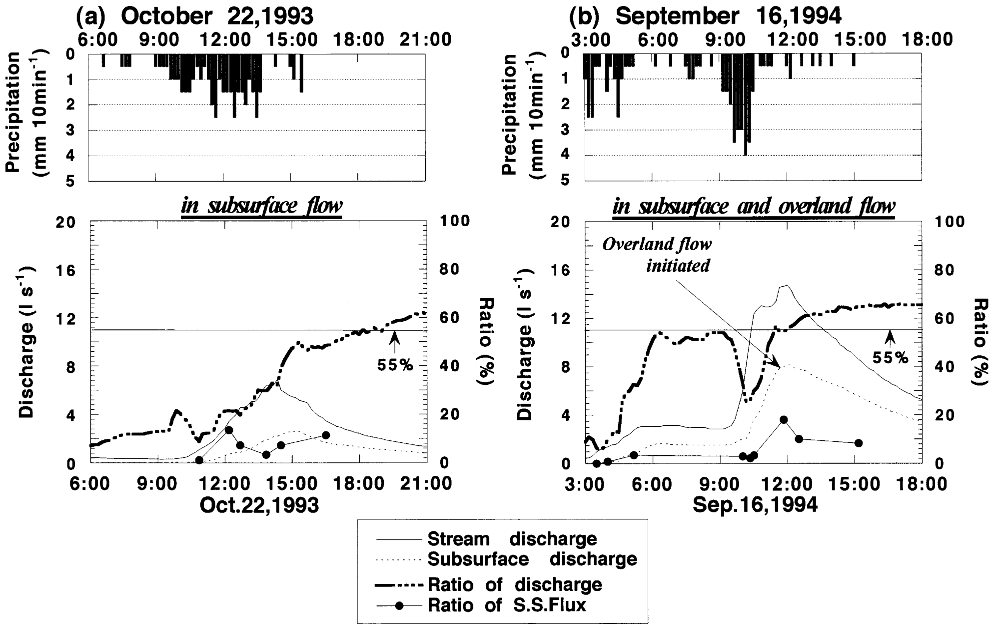

Figure 5. Relative importance of subsurface yields to total basin yields for water and sediment discharge on (a) 22 October 1993 and (b) 16 September 1994

overland flow initiation (Figure 5b, Table I). In comparison with both the drainage area contributing to the spring (55 per cent) and the ratio of water discharge from the valley head which exceeded 55 per cent during the falling limb of the stream hydrograph, the small effect on sediment yield from the total watershed occurs in the yield from the valley head. Accordingly, more than 80 per cent of the suspended sediment flux from the Jozankei Watershed originates from the stream bed and banks in these typical storms.

Shallow groundwater level, subsurface discharge and suspended sediment yield

Changes in subsurface discharge from the spring and shallow groundwater level in well W1 during the storms clearly show variations which coincided in time (Terajima *et al.*, 1996a). From these consistent data trends, the relationship between subsurface discharge and the shallow groundwater level in well W1 is easily analysed for the same time periods. However, well W3 rarely recorded shallow groundwater level during the observation period even if heavy rain occurred. In addition, shallow groundwater levels in well W2 were intermittent due to the rapid flow of subsurface water down to the lower part of the hollow, and the measurement of the level was frequently interrupted by technical problems with the potentiometer and the data logger. The small amount of data on changes in groundwater level, hardly accompanied by suspended sediment yield, disclosed that the characteristics of groundwater fluctuations in the head hollow are likely to appear as follows: the rising of groundwater level in well W2 appears at the same time as that in well W1; the peaks in the level in W2 precede the peak in W1 by about 1 h, and the fall of the level in W2 terminates about 3 h earlier than in W1.

Figure 6 (modified after Terajima *et al.*, 1996c) shows the relationships between hydraulic head gradient between well W1 and the spring, subsurface discharge, and suspended sediment yield during the rising limb of the storm hydrograph on 27 May and 16 September 1994, when groundwater levels in well W1 were completely measured without impedence by problems with the data logger.

Hydraulic head gradient is given by:

$$i_{(W1)}=h_{(W1)}l_{(W1)}^{-1} \tag{1}$$

where $i_{(W1)}$ is the hydraulic head gradient between well W1 and the spring (0·495 maximum), $h_{(W1)}$ is the shallow groundwater height in well W1 based on the level at the spring, and $l_{(W1)}$ is the horizontal distance between the spring and W1 (9·37 m).

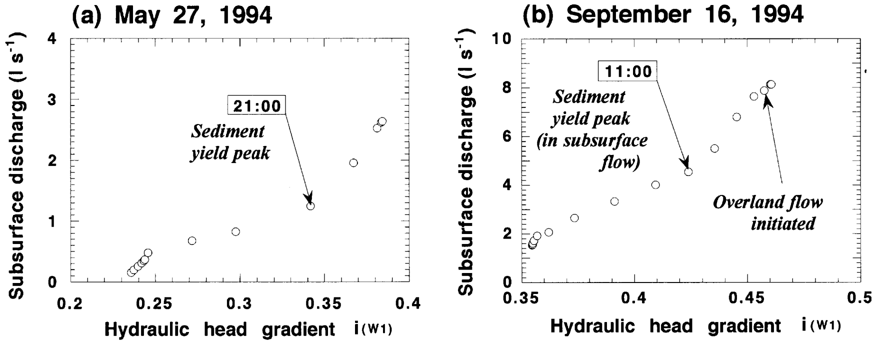

Figure 6. Relationship between hydraulic head gradient, subsurface discharge, and suspended sediment yield on (a) 27 May and (b) 16 September 1994 (modified after Terajima *et al*., 1996c)

Subsurface discharge tended to show concave curvilinear correlations from 0·25 to 0·39 of the hydraulic head gradient on 27 May and from 0·36 to 0·45 on 16 September. On 16 September, overland flow initiated in the rill running between well W1 and the spring when the correlation line changed convexly near 0·45. Suspended sediment reached a peak at 21:00 on 27 May and at 11:00 on 16 September and both peak times coincided well with the gradient changes into the concave correlation lines. Gradient changes into the more concave curvilinear correlations were hardly observed after the sediment peaks.

Subsurface flow via the soil matrix is classified by Reynolds number (R_e) into the following two situations: (1) $R_e \leq 10$, laminar flow; (2) $R_e > 10$, turbulent flow. Reynolds number for subsurface flow is given by:

$$R_e = v d \upsilon^{-1} \tag{2}$$

where v is the subsurface flow velocity ($v = Ksi$), d is the soil particle diameter, and υ is the kinematic viscosity. Insertion of the following three parameters into Equation 2 gives the maximum R_e for subsurface flow in the head hollow of the Jozankei Watershed: (1.) $0{\cdot}495 \times 10^{-3}$ m s^{-1} of the maximum v (10^{-3} m s^{-1} in maximum Ks and 0·495 in maximum $i_{(W1)}$); (2.) 5 mm of the maximum d (for the maximum diameter of fine pebble); and (3.) $1{\cdot}310 \times 10^{-6}$ m^2 s^{-1} of the minimum υ (for 10°C corresponding to the maximum subsurface flow temperature in the Jozankei Watershed). Consequently, the maximum R_e is 1·89. Subsurface flow is almost laminar during the storm and the curvilinear correlation in Figure 6 must be interpreted by Darcy's law. However, the linear correlation in the relationship between hydraulic head gradient and subsurface discharge can merely be explained by Darcy's law. Accordingly, subsurface flow indicating the curvillinear correlation in Figure 6 must be due not to Darcy's law but to the other kinematic law.

In the Jozankei Watershed, subsurface discharge is directly affected by changes in the drainage capacity of the sedimentary soil in the head hollow resulting from macropore volume (Terajima *et al*., 1996a). The concave curvilinear correlation of subsurface drainage with hydraulic head gradient (Figure 6) corresponds to an optimum drainage condition where preferential flow networks, including soil pipes, drain subsurface water from the hollow. The convex curvilinear correlation corresponds to conditions of insufficient subsurface drainage capacity of the soil. These two types of drainage conditions are also shown in plots of subsurface discharge versus hydraulic head gradient for various snow-melt periods in the hollow from April to May 1994. Gradient changes into the concave curvilinear correlation accompany the peak in suspended sediment discharge (Terajima *et al*., 1996c). Therefore, the sediment peak preceding the peak in subsurface discharge affects the sudden increase in the subsurface drainage capacity of the hollow during the rising limb of the hydrograph, and interacts with the subsurface flow system in the head hollow between well W1 and the spring.

Consequently, the fine-grained particles occurring between well W1 and the spring certainly affect the sediment peak at the spring resulting from subsurface hydraulic erosion caused by preferential flow (including pipe flow). That is, this preferential flow causes sediment discharge during storm runoff as well as the indicated macropores for sediment and solute transport in subsurface flow (e.g. Pilgrim and Huff, 1983; Tsuboyama *et al*., 1994).

DISCUSSION

Suspended sediment discharge and rate of change in subsurface discharge

Rate of change in discharge (dQ/dt, where d is differential, Q is stream discharge, and t is time) is an important parameter for describing suspended sediment yield following road construction and logging in a second-order drainage basin, and hydrograph characteristics, such as dQ/dt, aid the explanation of the variability of observed suspended sediment concentration (Anderson and Potts, 1987). Sediment yield during the early period of storm discharge results from rapid rising of the sapping force associated with subsurface flow acceleration (Namiki *et al*., 1993).

Therefore, correlations between rate of change in subsurface discharge ($1 s^{-2}$), changes in suspended sediment concentration and flux offer useful knowledge for understanding more fully suspended sediment discharge in subsurface flow, since the rate of change in subsurface discharge is a function of subsurface flow velocity (that is, $dQ/dt = dAv/dt$, where A is the flow area and v is the flow velocity) and the effect of dv/dt on subsurface hydraulic erosion is supported physically by Newton's law ($F = m dv/dt$, where F is the body force, m is the body mass, and dv/dt is the acceleration). However, the precise measurement of subsurface flow velocity is often difficult in the field, owing to the complex routes of subsurface flow. Accordingly, dv/dt is not usually applied to analyse sediment production, and dQ/dt is preferable for indicating erosion force caused by subsurface flow.

Figure 7 shows the results of two cases on 22 October 1993 and 16 September 1994. Initial change in suspended sediment concentration, in both cases, was consistent with initial rise in rate of change in subsurface discharge. The maximum value of suspended sediment concentration on 22 October 1993 mostly corresponded with the fourth peak in the rate of change (arrow in Figure 7a). However, the rate of change in subsurface discharge and suspended sediment concentration exhibited a poor correlation after the fourth peak in the rate of change. On the contrary, in both cases, changes in suspended sediment flux in subsurface flow were precisely consistent with variations in the rate of change in subsurface discharge.

Figure 8 shows the relationships between rate of change in subsurface discharge, suspended sediment concentration and flux during the rising limb of the hydrograph (including both the acceleratory and deceleratory rising limb; see Figure 10a and below for definition of terms) on 22 October 1993 and 16 September 1994. The linear correlation coefficient (r) of suspended sediment concentration was 0·52 and 0·66 on 22 October and 16 September, respectively. In contrast, the correlation coefficient of suspended sediment flux was 0·88 and 0·91 on 22 October and 16 September, respectively. Accordingly, in order to understand physically suspended sediment discharge in subsurface flow from the head hollow, suspended sediment flux is a better indicator of sediment yield process than the concentration.

Table II shows the linear correlation coefficients for the relationship between rate of change in subsurface discharge and suspended sediment flux during the rising limb in the observed eight storms. The minimum value of linear correlation coefficient was 0·88 on 22 October 1993. Consequently, at least during the rising limb of the storm hydrograph, erosion processes associated with the rate of change in subsurface discharge lead to changes in suspended sediment flux. If suspended sediment flux during the deceleratory rising limb ($dQ/dt \cdot d/dt < 0$, which shows the convex hydrograph, see Figure 10a) is ignored, the correlation coefficients in Figure 8b and Table II are modified to 0·96 and 0·97 for the storms on 22 October 1993 and 16 September 1994, respectively. That is, suspended sediment flux during the deceleratory rising limb is distributed in the upper part above the linear correlation line for every storm (Terajima *et al*., 1996b) as shown in Figure 8b. Thus linear correlation, in principle, should be applied during the acceleratory rising limb of the hydrograph ($dQ/dt \cdot d/dt \geq 0$, which shows the concave hydrograph, see Figure 10a). By rearranging the results in Figure 8b and Table II, the following equation emphasizes the process of suspended sediment discharge in subsurface flow for the acceleratory rising limb of the hydrograph at which subsurface hydraulic erosion occurs and both the production and transformation of suspended sediment are caused:

$$S = \alpha\{dQs/dt - (dQs/dt)_0\} \tag{3}$$

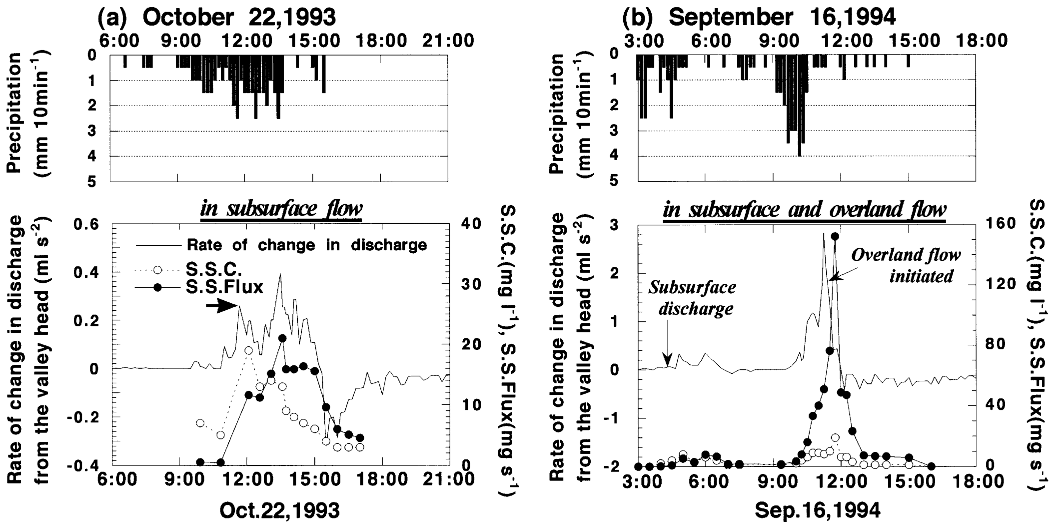

Figure 7. Rate of change in subsurface discharge, changes in concentration (SSC) and flux (SSFlux) of suspended sediment on (a) 22 October 1993 and (b) 16 September 1994

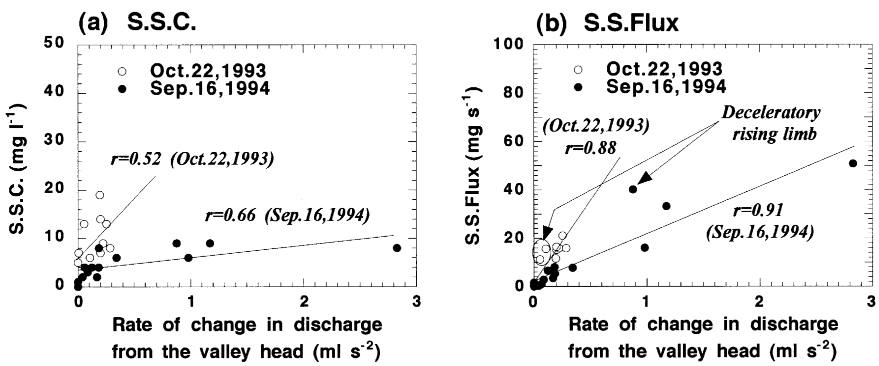

Figure 8. Relationship between rate of change in subsurface discharge and (a) suspended sediment concentration (SSC) and (b) flux (SSFlux) during the rising limb of the hydrograph on 22 October 1993 and 16 September 1994

where S is suspended sediment flux, α is a coefficient, Qs is subsurface discharge (flow rate), $\mathrm{d}Qs/\mathrm{d}t$ indicates rate of change in subsurface discharge, and $(\mathrm{d}Qs/\mathrm{d}t)_0$ is the threshold value to produce suspended sediment.

Relationship between α and initial subsurface discharge

From the dimensional analysis, coefficient α in Equation 3 gives information containing the relation of inverse proportion to subsurface discharge (s l^{-1}; see Table II). Additionally, the initial condition of suspended sediment yield associated with subsurface discharge affects α on account of the different gradient of the correlation lines (Figure 8b). This reveals that α is different in every storm (Table II) and suggests that changes in suspended sediment flux depend on the status of sediment supply in every storm. In other words, mobility of the head hollow soil before the storm influences the process of suspended sediment production in subsurface flow. Therefore, the relation between α and initial subsurface discharge prior to the storm runoff provides useful hints regarding suspended sediment discharge in subsurface flow; initial subsurface discharge is the suggestive parameter to argue subsurface flow velocity and flow area in the sedimentary soil before the storm.

Table II and Figure 9 show the relationship between α and initial subsurface discharge. Coefficient α is inversely correlated with initial subsurface discharge and exhibited rare seasonal variation. Although much subsurface discharge occurred during the meltwater season in 1994 and 1995, sediment discharge was scarcely

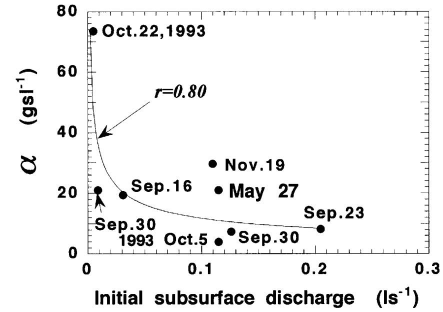

Figure 9. Coefficient α distribution associated with initial subsurface discharge

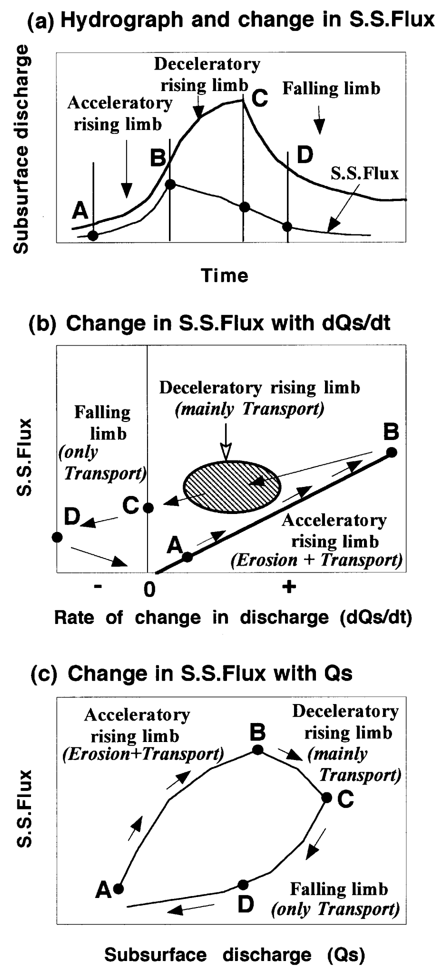

Figure 10. Conceptual diagram to explain the clockwise hysteresis loop in the relationship between subsurface discharge and suspended sediment flux. Diagram (b) was modified after Terajima *et al*., 1996b

measured ($\alpha = 0$) except in the case of meltwater initiation (Terajima *et al*., 1996c) because of very large initial subsurface discharge (about $2\,l\,s^{-1}$). Suspended sediment, therefore, tends to be low when the subsurface flow velocity prior to the runoff event is large.

Argument about clockwise hysteresis loop in suspended sediment discharge

If supply and availability (Walling and Webb, 1982) of suspended sediment is ignored, ‘Erosion (or Production)’ and ‘Transport’ must primarily characterize the processes of suspended sediment yield in subsurface flow; the relationship between ‘Erosion (or Production)’ and ‘Transport’ must determine the modes of suspended sediment yield in subsurface flow. The fact that suspended sediment was measured at the spring outlet indicates that the sediment has been eroded and produced according to Equation 3 and has been transported rapidly via the soil macropores without being trapped in drainage networks in the sedimentary soil. Accordingly, the clockwise hysteresis loop in the relationship between subsurface discharge and suspended sediment yield is possibly summerized as shown in Figure 10, based on the aspects on ‘Erosion (or Production)’ and ‘Transport’ (Figure 10b is modified after Terajima *et al*., 1996b).

Changes in suspended sediment flux resulting from subsurface hydraulic erosion are caused according to Equation 3 during the acceleratory rising limb of the hydrograph (between A and B in Figures 10a,b) which is chiefly observed at the initial stage in storm runoff. Thus, during the initial rising limb of the hydrograph, subsurface hydraulic erosion produces suspended sediment particles and subsurface flow transports them. That is, ‘Erosion (or Production)’ and ‘Transport’ of suspended sediment simultaneously occur in the head hollow during the acceleratory rising limb, and drastic sediment production arises from the spring, with increasing subsurface discharge (see Figure 10c). Since the peak in suspended sediment affects the subsurface flow system between well W1 and the spring (Figure 6), the sediment forming the peak chiefly originates from the subsurface portion near well W1. Accordingly, the production of suspended sediment prior to the sediment peak (between A and B in Figure 10c) must come mostly from the lower part of the hollow between well W1 and the spring.

However, because of the reduced erosion (or production) force of subsurface flow resulting from decreased dQs/dt during the deceleratory rising limb (between B and C in Figures 10a,b), ‘Transport’ of suspended sediment must be more important than ‘Erosion (or Production)’ and occurred mainly during increased subsurface discharge than during the initial acceleratory rising limb. Since gradient changes into the more concave correlation were hardly observed after the sediment peak (Figure 6), suspended sediment measured after the sediment peak scarcely affected the subsurface flow system between well W1 and the spring. That is, suspended sediment measured during the deceleratory rising limb (Figures 10b,c) originates from the upper subsurface portion of the hollow above well W1, and the sediment may come, with a time lag, to dQs/dt measured at the spring.

During the falling limb, negative dQs/dt (Figure 10b) in the any subsurface portion of the hollow causes no ‘Erosion (or Production)’ of suspended sediment. Only ‘Transport’ accompanied with decreased subsurface discharge produces the residual sediment in the hollow. Consequently, the clockwise hysteresis loop appears in the process of suspended sediment discharge in subsurface flow (Figure 10c).

CONCLUSIONS

Suspended sediment discharge in subsurface flow from the head hollow of the experimental watershed supported the close relationship between subsurface hydrology and soil movement in the head water, and exposed the following characteristics.

Neither concentration ($mg\ l^{-1}$) nor flux ($mg\ s^{-1}$) of suspended sediment correlated with subsurface discharge ($l\,s^{-1}$). Furthermore, the suspended sediment concentration showed a poor correlation with the rate of change in subsurface discharge ($l\,s^{-1}$) during the rising limb of the hydrograph. On the contrary, suspended sediment flux during the acceleratory rising limb showed a close correlation with rate of change in subsurface discharge, and the coefficient α in Equation 3 depended on initial subsurface discharge prior to the storm runoff. ‘Erosion (or Production)’ and ‘Transport’ of suspended sediment during the acceleratory rising limb occur according to Equation 3. Thus, suspended sediment flux associated with the rate of change in subsurface discharge (dQs/dt) and initial subsurface discharge prior to the storm are the appropriate parameters to disclose suspended sediment production in subsurface flow and to explain the clockwise hysteresis loop in the relationship between subsurface discharge and suspended sediment yield during the storm runoff.

Understanding the physical mechanism in suspended sediment yield encourages the universal application of Equation 3 for suspended sediment and bedload discharge in subsurface flow in the many slopes or head waters underlain by other geology. More data on suspended sediment discharge should be available to identify the accurate source of the sediment, including the unsaturated zone in the slope as well as the sediment source during the falling limb of the hydrograph at which the transportation force of subsurface flow possibly and principally determines the process of suspended sediment movement.

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